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January 22, 1997

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Dr. Edwin Barker
Technical Officer
Code SLD
NASA Headquarters
Washington DC 20546-0001

Re: Final Report for "Generation Mechanisms UV and X-ray Emissions During SL9 Impact"
(SwRI project #15-7638; NASA grant NAGW-4788)

Dear Dr. Barker,

The purpose of this grant was to study the ultraviolet and X-ray emissions associated with the impact of comet Shoemaker-Levy 9 with Jupiter. This grant was a subtask of a larger grant that was awarded to the University of Michigan. The University of Michigan task was primarily focused on theoretical calculations. The NAGW-4788 subtask was to be largely devoted to determining the constraints placed by the X-ray observations on the physical mechanisms responsible for the generation of the X-rays. As a result of a change in the original PI of the University of Michigan task, there was some difficulty in completing the combined theoretical/observations analysis. I summarize below the ROSAT observations and suggest a physical mechanism that can plausibly account for the observed emissions. It is hoped that the full set of activities can be completed at a later date.

Further analysis of the ROSAT data acquired at the time of the impact was necessary to define the observational constraints on the magnetospheric-ionospheric processes involved in the excitation of the X-ray emissions associated with the fragment impacts. This analysis centered around improvements in the pointing accuracy and improvements in the timing information.

Additional pointing information was made possible by the identification of the optical counterparts to the X-ray sources in the ROSAT field-of-view. Due to the large number of worldwide observers of the impacts, a serendipitous visible plate image from an observer in Venezuela provided a very accurate location of the present position of the X-ray source, virtually eliminating pointing errors in the data. Once refined, the pointing indicated that the two observed X-ray brightenings that were highly correlated in time with the K and P2 events were brightenings of the X-ray aurora (as identified in images prior to the impact). The X-ray aurora appears to be magnetically connected to the Io plasma torus, with a longitude peak in the northern hemisphere brightness at an SIII longitude between 130 and 150 degrees. These X-ray data are shown in Figure 1 (intensity in Rayleighs). Figure 1a is an image of the X-rays, organized in solar local time and planetary latitude; Figure 1b is a Mercator projection showing the emissions organized in SystemIII longitude and latitude. Also indicated are auroral ovals for the last closed field line and the position of Io's orbit mapped along magnetic field lines to the planet, the impact site (white star) and its magnetic conjugate point (orange star), and the position of the Io flux tube (red star).



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The other relevant point was the timing of the events. Our earlier analysis of the K impact was refined and compared to Galileo (Chapman et al., 1995) and ground-based infrared images from the Australian National Observatory (ANO) (McGregor et al., 1996). The results that appear in Figure 2 remain unchanged from the original figure in the Waite et al., 1995 *Science* paper (see Appendix A). They indicate that the X-rays began at precisely the same time as the infrared precursor event seen at ANO and about three minutes prior to the impact of the main bolide as imaged by the Galileo imager. This important piece of information suggests that smaller fragments (outriders from the K fragment) interacted with the upper atmosphere and triggered the X-rays prior to the main bolide impact. The hypothesis that smaller fragments depositing their energy in the upper atmosphere were primarily responsible for the X-rays is reinforced by the fact that the P2 event was bright and well-defined at X-ray wavelengths, but was never seen by HST imaging (thus it appears that the fragment was torn into smaller fragments prior to impact (Hal Weaver, private communication)).

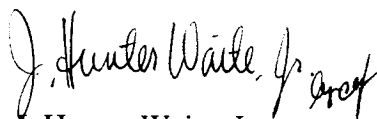
The limited observational evidence that we have suggests the following scenario for X-ray generation. Smaller fragments deposit the bulk of their energy in the upper atmosphere and create magnetohydrodynamic shocks (Brecht et al., 1994) and subsequently Alfvén waves that propagate near c into the ionosphere and magnetosphere of Jupiter. These Alfvén waves change speed (and thus interact) with the plasma medium in the Io torus near Io and in the auroral ionosphere, where plasma densities are dramatically increased. These interactions trigger/enhance existing pitch angle scattering of energetic sulfur and oxygen ions, which subsequently precipitate into the atmosphere and produce the X-ray emissions.

These results were reported in a poster at the SL-9 Jupiter impact conference held at the Meudon Observatory in July of 1996.

References

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Chapman, C. R., et al., Preliminary results of Galileo direct imaging of SL-9 impacts, *Geophys. Res. Lett.*, 22, 1561, 1995.
McGregor, P.J., P. D. Nicholson, and M. G. Allen, CASPIR observations of the collision of comet Shoemaker-Levy 9 with Jupiter, *Icarus*, 121, 361, 1996.
Waite, J. H., Jr., et al., ROSAT observations of x-ray emissions from Jupiter during the impact of comet Shoemaker-Levy 9, *Science*, 268, 1598, 1995.

Sincerely,

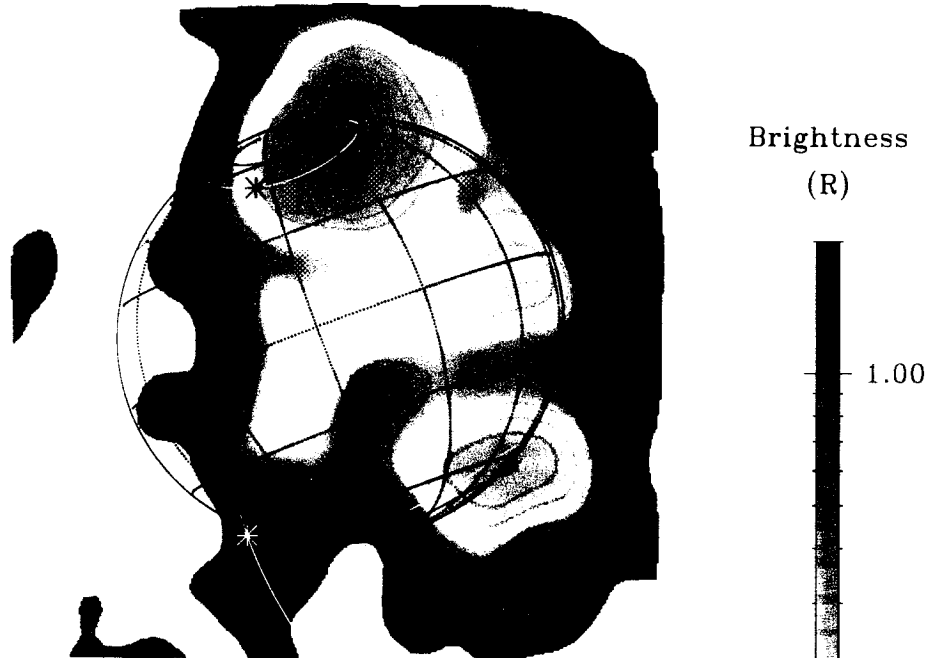


J. Hunter Waite, Jr.

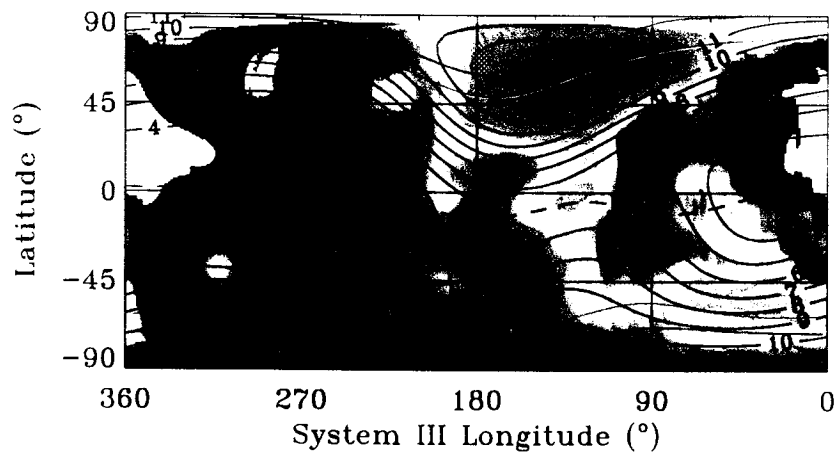
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ROSAT Jupiter X-Rays – During Impacts

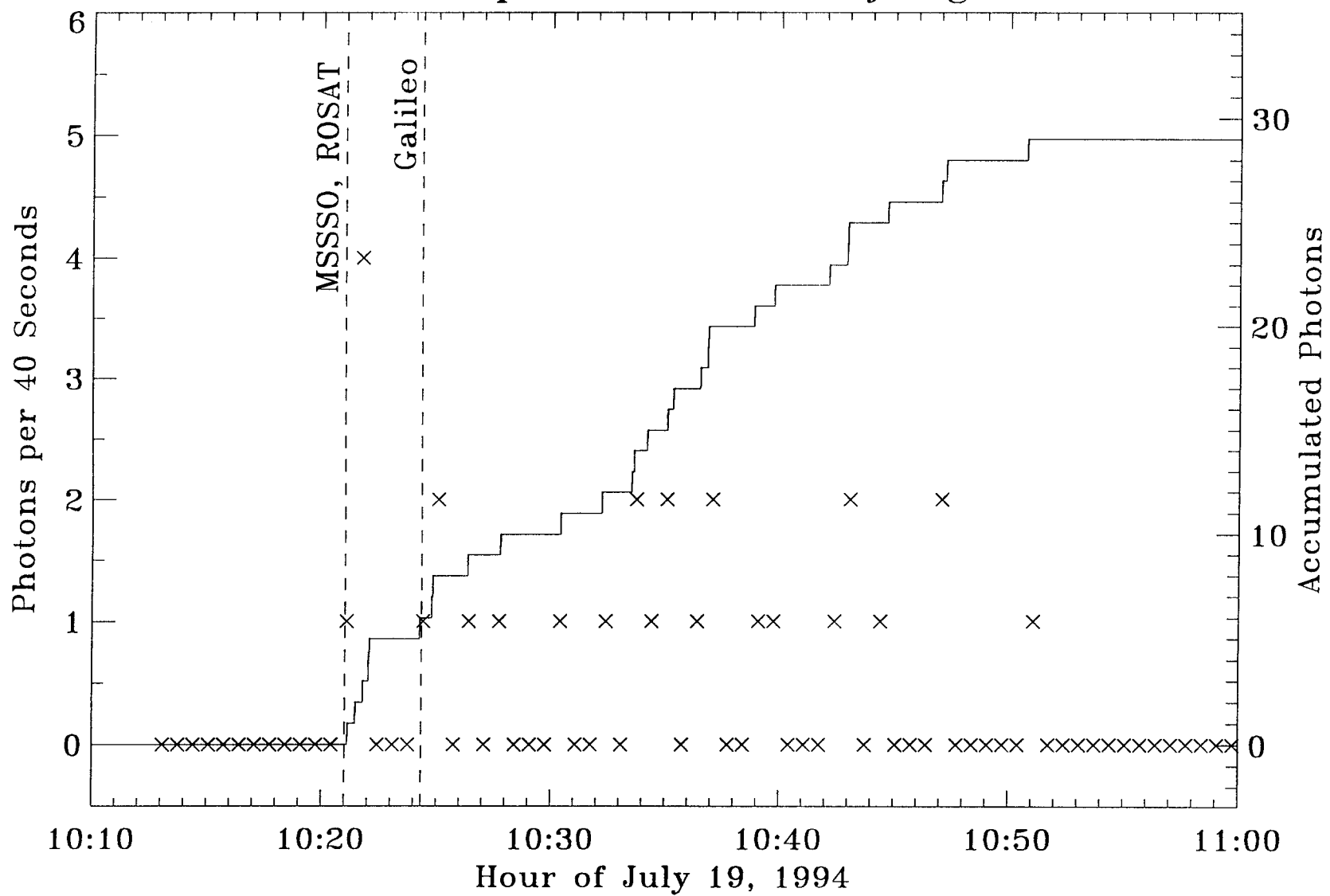
a)



b)



ROSAT K Impact Jovian X-Ray Light Curve



APPENDIX A

ROSAT Observations of X-ray Emissions from Jupiter During the Impact of Comet Shoemaker-Levy 9

J. H. Waite Jr.,* G. R. Gladstone, K. Franke, W. S. Lewis, A. C. Fabian, W. N. Brandt, C. Na, F. Haberl, J. T. Clarke, K. C. Hurley, M. Sommer, S. Bolton

Röntgensatellit (ROSAT) observations made shortly before and during the collision of comet Shoemaker-Levy 9 with Jupiter show enhanced x-ray emissions from the planet's northern high latitudes. These emissions, which occur at System III longitudes where intensity enhancements have previously been observed in Jupiter's ultraviolet aurora, appear to be associated with the comet fragment impacts in Jupiter's southern hemisphere and may represent brightenings of the jovian x-ray aurora caused either by the fragment impacts themselves or by the passage of the fragments and associated dust clouds through Jupiter's inner magnetosphere.

Auroral x-ray emissions from Jupiter's high magnetic latitudes have been reported in previous studies (1, 2). Although the identity of the particles responsible for these emissions has not been conclusively established, the evidence favors sulfur and oxygen ions originating in the Io plasma torus and accelerated in the outer jovian magnetosphere (1, 2). Auroral ion precipitation is believed to result from pitch angle scattering into the loss cone as the accelerated ions diffuse inward (3). In this report we present recent observations made with the ROSAT high-resolution imager (HRI) of intense x-ray emissions from Jupiter's high northern latitudes. These emissions appear to be associated with the impact of fragments of comet Shoemaker-Levy 9 and probably represent a brightening of the jovian x-ray aurora caused either by the impacts themselves or by the passage of the fragments and the associated dust cloud through the inner magnetosphere.

The fragments of Shoemaker-Levy 9 plunged into Jupiter's upper atmosphere at about -40° latitude during the period 16 to 22 July 1994. On 13, 14, and 15 July, the ROSAT HRI acquired preimpact data for comparison with observations made during the impacts. Additional data were acquired from 18 to 22 July, during or near the times

of the impacts of fragments K, P, R, S, and W. The x-ray photons were individually detected and time-tagged, allowing us to compensate for the motion of both Jupiter and the ROSAT spacecraft during the observation period and to synthesize images of Jupiter (4).

To identify variations associated with the impacts, we created a light curve (Fig. 1) by extracting a small (70 arc sec by 70 arc sec) field centered on the disk of Jupiter from the larger HRI field of view (40 arc min by 40 arc min). Photons arriving in the small field of view were summed over each ROSAT orbit and divided by the corresponding exposure time (5). The light curve shows considerable variability, with a noticeable brightening at the times of the K and P2 impacts (6).

We investigated the statistical significance of the photon count rate increases as a function of time by performing two standard statistical tests: a Kolmogorov-Smirnov test and its close derivative, the Kuiper test (7). We chose these two tests because they are independent of binning start time and width, which can make Poisson-distributed events appear artificially strong. The test space was the northern auroral zone,

which we defined as $-15 \text{ arc sec} < x < 15 \text{ arc sec}$ and $5 \text{ arc sec} < y < 25 \text{ arc sec}$, where x and y are measured from the center of Jupiter toward decreasing jovian longitude and increasing jovian latitude, respectively. We first compared our preimpact data (29,791 s) for 13 to 15 July with earlier data (12,324 s) from May 1992 (2). According to both tests, the likelihood that the two data sets were drawn from the same population is $\sim 50\%$. We then compared the entire set of data acquired during the impacts (33,267 s) with both our preimpact data and the 1992 data. The probability is less than 5×10^{-5} that the impact data are from the same statistical population as the preimpact data and less than 1% that they are from the same population as the 1992 data. As a further test, we combined the 1992 data and the 1994 preimpact data to create a new baseline data set, with which we compared the data for the K (~ 2200 s) and P2 impacts (~ 1900 s). The probability that the K impact data and the new baseline data are from the same distribution is less than 8×10^{-5} , and for the P2 impact data, the probability is less than 2×10^{-5} . The results of our analysis indicate that the high count rates detected by HRI during the impact period, particularly near the times of the K and P2 impacts, are unique.

We can examine the timing and intensity of the emission associated with the K impact more closely than is possible in the case of the P2 impact because of the relative intensity of the K impact-associated emission and the availability of correlative data on the K impact from Galileo and both ground-based and Earth-orbiting observatories. In the high-resolution light curve shown in Fig. 2, the x-ray burst occurs at 10:21:25 UT, at approximately the same time as the detection by ground-based observers in Australia of faint emissions at $2.34 \mu\text{m}$ from the K impact site (10:21:13 UT) (8). The infrared emissions are first seen in a frame at 10:20:25 to 10:20:57 UT with a faint precursor event that brightens slightly in the following three frames between 10:21:13 and 10:23:19 UT and then

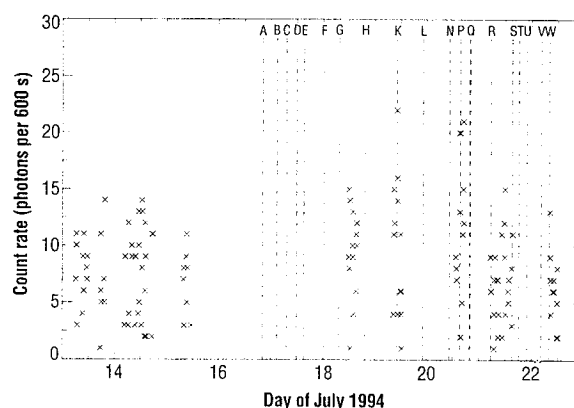


Fig. 1. The ROSAT x-ray light curve for a 70 arc sec by 70 arc sec region centered on Jupiter. The crosses indicate the average count rates from the region during each orbit of Jupiter observations in July 1994. The comet fragment impact times are indicated with vertical dashed lines.

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brightens considerably after 10:23:35 UT. Interestingly, both the x-ray and 2.34- μm emissions began about 3 min before the detection, at 0.89 μm , of the K fragment

fireball by the Galileo Solid State Imager (SSI). The SSI data for the K impact show that the event began at 10:24:13 UT and lasted about 52 s (9). The 3-min difference

in time of observation between the beginning of the x-ray burst and the 2.34- μm precursor, on the one hand, and the flash observed by the SSI, on the other, has not been explained. For our analysis, we define the K impact x-ray event as the eight photons detected over the 220-s interval between the beginning of the x-ray burst at 10:21:25 UT and the end of the flash observed by Galileo.

Figure 3 shows images of Jupiter as seen at x-ray wavelengths before, during, and after both the K and P2 events. To produce these images, data acquired during the observing segments surrounding the K and P2 fragment impacts were smoothed by HRI's point spread function (5). The nominal point spread width is 5 to 6 arc sec, with a comparable nominal uncertainty in pointing; however, the identification and measurement of two stars within the ROSAT field of view during the impact time period make it possible to reduce the pointing uncertainty to less than 3 arc sec (10). Given this uncertainty, the brightest x-ray emissions appear to occur near System III longitude $\lambda_{\text{III}} = 170^\circ$ and $+50^\circ$ latitude during the K event, and near longitude $\lambda_{\text{III}} = 180^\circ$ and $+70^\circ$ latitude during the P2 event (the differences in latitude and longitude between the two emission regions are within the 3-arc sec pointing uncertainty of the observations). Interestingly, the K emission peak is located near the foot of the Io flux tube (IFT: $\lambda_{\text{III}} = 186^\circ$, latitude = $+50^\circ$), a known source of auroral emissions (11). The location of the P2 peak is not as close to the foot of the IFT (IFT: $\lambda_{\text{III}} = 273^\circ$, latitude = $+75^\circ$). The occurrence of the K burst near the foot of the IFT may or may not be coincidental and indicative of IFT involvement in the generation of the emissions. In contrast to the transient ultraviolet emissions observed by the Hubble Space Telescope (HST) 45 min after the K impact (12), the x-ray emissions associated with the K event do not occur near the northern magnetic conjugate point of the impact site ($\lambda_{\text{III}} = 269^\circ$, latitude = $+38^\circ$), as we initially reported (13) before our final pointing determination was made.

Observations of the jovian aurora at ultraviolet (UV) and infrared (IR) wavelengths show the aurora to exhibit both rotational and temporal variations in emission intensity (14). Although less extensive than the data on the UV and IR auroras, ROSAT x-ray data acquired in 1992 indicate that the x-ray aurora displays a rotational or longitudinal variability consistent with that of the UV and IR aurora, with a peak in emission intensity near the central meridian longitude (CML) range $\lambda_{\text{III}} = 180^\circ$ to 200° (2). The fact that the x-ray bursts observed near the times of the K and P2 impacts occur near this longitude range

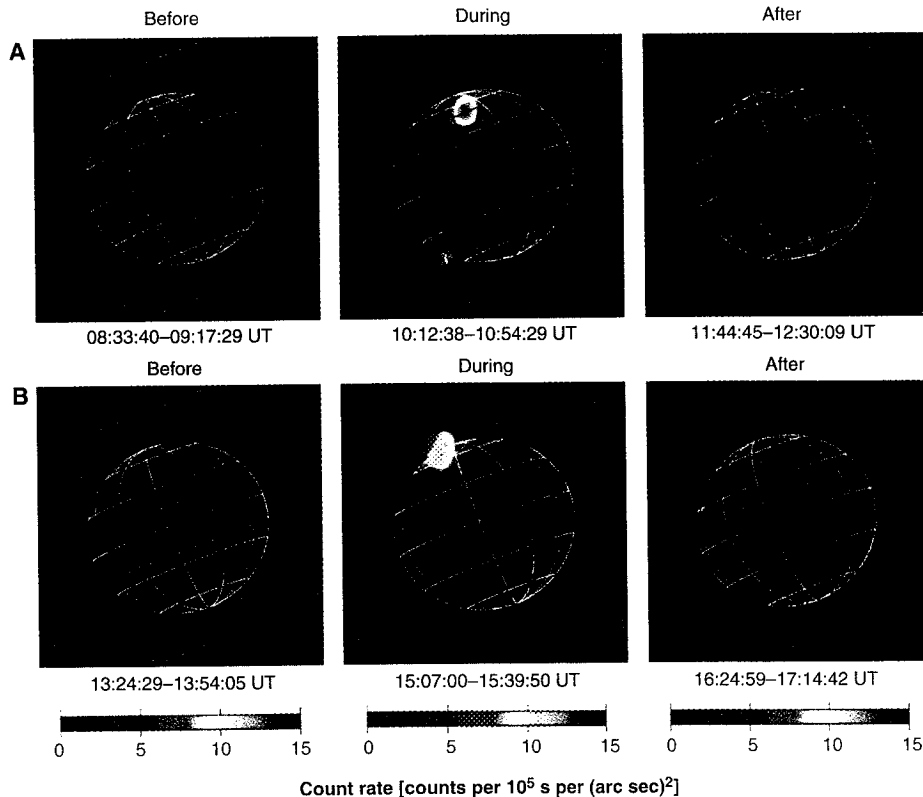
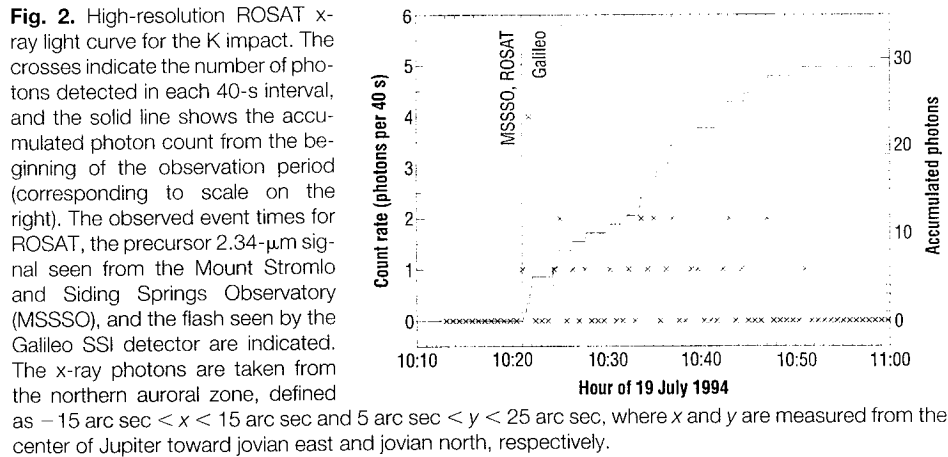


Fig. 3. X-ray images of the signal in a 70 arc sec by 70 arc sec region centered on Jupiter for ROSAT orbits before, during, and after the (A) K and (B) P2 impacts. The images have been smoothed by the HRI point spread function, and the absolute brightness scale is shown at the bottom. A latitude-longitude grid shows the orientation of Jupiter at the midpoint of each exposure interval (except for the "during" panel of the K impact event, for which the grid represents Jupiter at the impact time). The grid spacings are 30° in both latitude and System III longitude, with the 180° meridian in green. The north and south footprints of the Io plasma torus and the magnetotail region ($L = 30$) are indicated by the red and yellow lines, respectively. The orange asterisk, when visible, shows the estimated location of the IFT footprint in the northern hemisphere. In the "during" panel for the K impact, the green asterisk shows the magnetic conjugate region to the K impact site, and the trajectory of the K fragment and its position 3 min before impact are shown by a white line and asterisk, respectively. The dashed line boxes in the "before" panels mark the north and south auroral regions used for the statistical studies described in the text. The small (3 arc sec) circle in the upper right corner of the "during" panels represents a conservative estimate of the ROSAT pointing uncertainty.

raises the possibility that HRI simply detected normal, longitude-dependent increases in the intensity of Jupiter's x-ray aurora. To test this possibility, we combined preimpact x-ray data with impact-period data (minus the bright events associated with the K and P2 impacts) to produce a rotational light curve (Fig. 4) and calculated an average peak emission intensity at a CML of $\lambda_{III} = 170^\circ$ to 180° of 0.006 count per second. We then compared this count rate with that observed in association with the K and P2 events. According to Poisson statistics, the probability is 6×10^{-5} that the 220-s eight-photon burst associated with the K impact was from the rotational light curve of the auroral oval; for the P2 event, the probability is 3×10^{-4} .

Thus, the K and P2 events are statistically different from increases expected of the normal x-ray aurora near CMLs of $\lambda_{III} = 180^\circ$ to 200° . We cannot, however, rule out the possibility that we observed unusually bright auroral events that occurred only coincidentally near the time of the K impact. Dramatic brightenings of the UV aurora have been observed by HST (15), for example, and it is possible that ROSAT detected a similar event at x-ray wavelengths. Although our x-ray data are too limited to permit us to dismiss this possibility, it seems highly unlikely that two such events would both occur coincidentally at or very near the times of fragment impacts. Moreover, observations by the International Ultraviolet Explorer suggest that the UV aurora—and by implication, the x-ray aurora as well—was quiet around the time of the K impact (16).

If, as our analysis indicates, the observed x-ray enhancements were indeed correlated with the fragment impacts, by what processes might they have been triggered? Possible emission mechanisms include electron bremsstrahlung or K shell emission from precipitating energetic sulfur and oxygen ions. Both mechanisms

have been proposed to explain the auroral x-rays observed previously by the Einstein Observatory and ROSAT (1, 2). Unfortunately, we have no statistically meaningful information from ROSAT about the energy spectra of the x-rays observed in association with the impacts (17) and no direct information about the energies of the precipitating particles. Whether ions or electrons, we assume that the fragment impacts did not directly energize the particles responsible for the emissions because of the timing of the x-ray events, but triggered particle precipitation from an existing reservoir of energetic charged particles in Jupiter's inner magnetosphere.

Whatever the particular emission mechanism, the processes responsible for the K and P2 x-ray events may have been triggered either by the impacts themselves or by the passage of the fragments and associated dust through Jupiter's inner magnetosphere. The fact that the x-ray emissions associated with the K event were detected about 3 min before the observation of the fireball by Galileo may indicate that the x-ray burst occurred before the actual impact and suggests that fragment-dust interactions with the inner magnetospheric plasma before impact were responsible for the observed brightening. However, at 3 min before impact, the K fragment was crossing field lines that map to lower latitudes and higher longitudes than those at which the emissions were observed (18). If a direct interaction between the fragments, dust, and the plasma within these L shells had been involved, the emissions would have occurred at these lower latitudes and higher longitudes. Instead, they occurred near the auroral zone latitudes and System III longitudes where the emission maxima of the normal UV aurora are also observed (19).

On the other hand, the faint precursor emission detected at 2.34- μm at about the same time as the beginning of the K x-ray

event suggests an interaction of the fragment or dust with Jupiter's upper atmosphere and ionosphere and thus a process triggered by the impacts themselves. Further, the absence of impact residue at visible wavelengths suggests that the P2 fragment dissipated high in the atmosphere (20), favoring a process involving the deposition of energy in the magnetosphere-ionosphere coupling region. Such a process might produce magnetohydrodynamic shocks capable of accelerating trapped radiation belt particles (21) or electromagnetic and plasma waves capable of interacting with the electrons and ion populations in the inner magnetosphere.

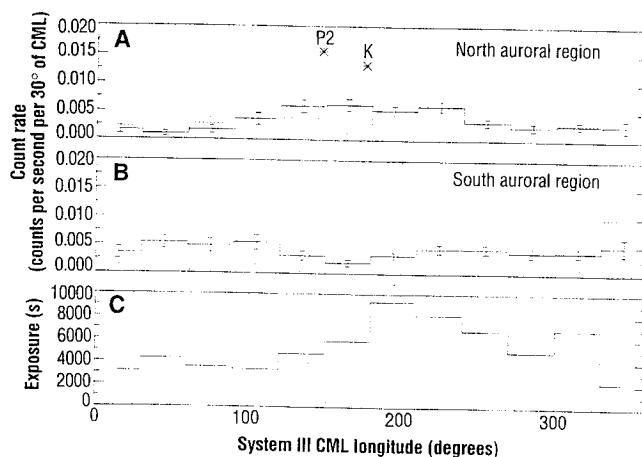
If the emissions had been caused by an impulsive, impact-induced process, the intensity maxima would likely have been correlated with the minimum in surface magnetic field strength. However, they appear to have occurred near longitudes where the magnetic field is strongest and the field gradients are inferred to be steepest (22). In the case of the UV aurora, the emission peaks in regions of steep negative gradients in the magnetic field strength have been attributed to processes involving gradient curvature drift (19). Drift is slow, however, requiring 60 jovian rotations for 1-MeV heavy ions to drift 360° , for example. A drift process thus cannot easily be invoked to explain precipitation events that occur nearly simultaneously with the impacts.

The x-ray enhancements observed by ROSAT were likely related to the impacts of the comet Shoemaker-Levy 9 fragments. The fact that the emission peaks were detected in a region where intensity enhancements occur in the normal UV aurora suggests that processes related to the comet fragment impacts caused a significant brightening of Jupiter's x-ray aurora. Identification of these processes, however, must await further synthesis of the data acquired during the comet impacts, the availability of more extensive data on jovian auroral x-ray emissions, and the availability of additional in situ plasma measurements from the Galileo mission. In addition, hard x-ray data acquired at the time of the K impact by the Earth-orbiting Compton Gamma Ray Observatory and the Solar X-ray/Cosmic Gamma Ray Burst Detector on the Ulysses spacecraft are being analyzed.

REFERENCES AND NOTES

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2. J. H. Waite Jr. *et al.*, *ibid.* **99**, 14799 (1994).
3. N. Gehrels and E. Stone, *ibid.* **88**, 5537 (1983).
4. Details of this method are presented in (2).
5. L. P. David, F. R. Harnden Jr., K. E. Kearns, M. V. Zombeck, in *The ROSAT High Resolution Imager* (U.S. ROSAT Science Data Center and Smithsonian Astrophysical Observatory, Cambridge, MA, 1995).

Fig. 4. (A and B) Rotational x-ray light curves for Jupiter. The solid line histogram and error bars show the ROSAT count rates averaged in 30° bins of central meridian longitude (CML), using all the July 1994 data except the orbits containing the K and P2 impacts, which are shown individually as asterisks. The dotted line histogram and error bars are from the May 1992 ROSAT data (2). The (A) north and (B) south auroral regions from which the data were taken are defined in Fig. 3. **(C)** The total exposure time acquired in each 30° CML bin.



Counts with pulse height analyzer channel numbers <4 (out of a 1 to 16 range) were eliminated to avoid contamination from UV emissions.

6. The x-ray emissions observed in association with the K and P2 impacts appear to display a longitude dependence similar to that of the UV aurora and to that postulated for the normal x-ray aurora (2). The longitude region within which they occurred was not visible to ROSAT at the times of the R and S fragment impacts, however, which may explain why no enhanced counts were detected in association with these events. ROSAT may have detected a weak signature near the time of the W impact; however, data collection did not start until about 6 min after the W impact. The relatively weak W signature may represent the waning tail of a more active x-ray emission period.
7. The Kolmogorov-Smirnov and Kuiper tests used in our analysis of the K and P2 observations are described in W. H. Press, S. A. Teukolsky, W. T. Vetterling, B. P. Flannery, *Numerical Recipes in FORTRAN: The Art of Scientific Computing* (Cambridge Univ. Press, Cambridge, ed. 2, 1992), pp. 617–622. Although we used both tests, we cite only the Kuiper statistics, which are more conservative (generally by a factor of 10) than the Kolmogorov-Smirnov statistics.
8. Information about the 2.34- μ m observations made at the Australian National University's Mount Stromlo and Siding Springs Observatory was kindly provided by P. McGregor, personal communication.
9. C. R. Chapman *et al.*, *Geophys. Res. Lett.*, in press.
10. ROSAT's normal pointing uncertainty of 5 arc sec (1σ) was considerably improved upon for our Jupiter observations by the fortuitous presence of two astrophysical x-ray point sources within the 40-arc min-diameter field of view. High-precision positions for the optical counterparts to the two sources near the time of the impacts were kindly provided to us by O. A. Naranjo (personal communication). One of the sources is at right ascension (RA) 14 hours, 13 min, and 5.14 s and declination (DEC) 12° , 1 arc min, and 24.4 arc sec and is identified as the star GQ Vir. The other source is at RA 14 hours, 12 min, and 39.1 s and DEC 12° , 9 arc min, and 10.8 arc sec and is unidentified in the visible. Using these positions, we corrected the ROSAT data by shifting the centroided counts from these two sources to the above positions. The final pointing accuracy appears to be good to within ± 1.5 arc sec.
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12. J. T. Clarke *et al.*, *ibid.* **267**, 1302 (1995).
13. J. H. Waite *et al.*, *Eos* **74** (suppl.), 404 (1 November 1994).
14. For data on the variability in the brightness of the UV and IR auroras, see T. A. Livengood, thesis, Johns Hopkins University (1991) and H. A. Lam, thesis, University College, London (1995).
15. J. C. Gérard *et al.*, *Science* **266**, 1675 (1994).
16. W. M. Harris *et al.*, in preparation; J. T. Clarke *et al.*, *Bull. Am. Astron. Soc.* **26**, 1100 (1994).
17. ROSAT's Position Sensitive Proportional Counter (PSPC) determines with a $\Delta E/E$ of 30% the energy E of incident x-ray photons over an energy range 0.12 to 2.1 keV. Unfortunately, PSPC observations were not made during the impact period. Limited inferences about particle energy can be made, however, on the basis of the ratios of HRI's low-energy pulse height analyzer (PHA) channels (4 to 5) to the higher energy channels (6 to 8) (5). The PHA ratio for the preimpact observations was 3.5 ± 0.9 ; the ratio for the x-rays detected during the 42 min surrounding the K event was 2.4 ± 1.6 .
18. J. E. P. Connerney, private communication. The K fragment trajectory in Jupiter's magnetosphere was calculated with the Goddard Space Flight Center O6 magnetic field model and magnetodisc model [J. E. P. Connerney, M. H. Acuña, N. F. Ness, *J. Geophys. Res.* **86**, 8370 (1981); J. E. P. Connerney, *ibid.* **98**, 18659 (1993)].
19. F. Herbert, B. R. Sandel, A. L. Broadfoot, *ibid.* **92**, 3141 (1987).
20. H. B. Hammel *et al.*, *Science* **267**, 1288 (1995).
21. S. H. Brecht, M. Pesses, J. G. Lyon, N. T. Gladd, S. W. McDonald, *Geophys. Res. Lett.*, in press.
22. See (19) and references therein.

23. We thank S. H. Brecht, I. de Pater, and A. J. Dessler for sharing unpublished results and for valuable discussions; O. A. Naranjo and N. Schneider for information relevant to pointing issues; D. Glicksberg for data on the K fragment trajectory; J. E. P. Connerney for plotting the K fragment trajectory across Jupiter's magnetic field lines; and G. J. Fishman and B. C. Rubin for the Compton Gamma Ray Observatory BATSE (Burst and Transient Source Experiment) data. We gratefully acknowledge the work of the ROSAT team. ROSAT is sup-

ported by the Bundesministerium für Forschung und Technologie. J.H.W. acknowledges support from the ROSAT Guest Observer Program (NAG5-2617) and from the National Aeronautics and Space Administration Planetary Atmospheres program (NAGW-3624). A.C.F. thanks the Royal Society, and W.N.B. thanks the National Science Foundation and the British Overseas Research Studentship Programme for financial support.

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